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Workshop Proposal: Scientific Exploration of Induced Seismicity and Stress (SEISMS)

Heather Savage
Lamont-Doherty Earth Observatory
Columbia University
61 Route 9W, Palisades, NY 10964
Phone: 845-365-8720
hsavage@ldeo.columbia.edu

Technical Report
1. SEISMS Meeting
1.1 Itinerary
The SEISMS workshop was held at Lamont-Doherty Earth Observatory, New York, USA, over three days from March 29-31, 2017. Attended by 86 participants from 10 countries, including representatives from industry, academia, and education (Figure 1), the workshop was sponsored by the International Continental Scientific Drilling Program (ICDP), the United States Geological Survey (USGS), and Southern California Earthquake Center (SCEC). The workshop included a series of keynote talks from experts in earthquake physics, borehole instrumentation and observatories, induced earthquakes, and active earthquake experiments, as well as group discussions concerning the need for an earthquake experiment, the scientific value of such an experiment, and the potential risks associated with inducing earthquakes.

Figure 1. SEISMS participants at Lamont-Doherty Earth Observatory, Columbia University. The conference included 86 participants from 10 countries.

1.2 Knowledge Gaps Between Earthquake Theory and Observation
The primary goal of the SEISMS workshop was to outline and prioritize critical unresolved questions in earthquake physics. The majority of these questions are centered on our current inability to scale theory based on laboratory experiments to natural faults, as well as our inability to incorporate real-world complexity into lab experiments and models.

Much of our understanding of earthquake nucleation is based on the rate-and-state friction laws, which predict that an earthquake will begin by slipping aseismically until the rupture reaches a critical size, h^*:

$$h^* \sim \frac{\mu L}{(b-a)(\sigma-p)} \qquad \textit{Equation 1}$$

where μ is rock shear modulus, L is the critical slip distance, σ is normal stress, p is pore pressure, and a and b are rate-and-state parameters (Rice, 1993; Scholz 1998; Ampuero and Rubin, 2008). Because we do not know how some parameters, such as L, scale from laboratory to natural fault, the nucleation patch size is unknown, but might range in size from 0.1-10 m and will vary significantly depending on effective stress resolved along the fault. It is unknown at this point whether the final earthquake size is a function of h^*. If it was, this would indicate that there is a fundamental difference between small and large earthquakes, as has been suggested estimating other earthquake parameters such as fracture energy (Viesca and Garagash, 2015). Measurements of the nucleation length scale, accelerations, or moment release during the initial stages of slip are needed to understand the growth of earthquakes. In order to capture these signals, instrumentation would need to be essentially within meters of the slip surface. Such observations could never be made from the surface.

In addition to earthquake initiation, the processes or conditions that cause earthquakes to either arrest or propagate to larger magnitudes remain unknown, which is primarily why earthquake magnitude cannot be predicted. Structural complexity is an aspect of faults whose effects on earthquake dynamics are unknown. Geometric complexities such as non-planarity have been invoked to serve as nucleation sites (asperities) as well as boundaries to rupture propagation. Fault complexity also affects the slip during an earthquake, efficiency of energy dissipation mechanisms, and the radiation of seismic energy (Dunham et al., 2011). Furthermore, hydraulic diffusivity changes both within the fault core as well as damage zones may have significant control on pore pressure gradients throughout the rupture, and may aid in rupture arrest and the promotion of slow aseismic slip rather than fast seismic slip. In addition to geometric complexity, the controls of materials properties on different regions of the fault, such as regions of preseismic, coseismic and afterslip, may not be constant through time or along strike.

1.3 Small to Large Scale In-situ experiments and the Accidental Experiment of Induced Seismicity

Planning for the SEISMS experiment will lean heavily on the lessons learned from the Rangely experiment conducted during the 1970s (Raleigh et al., 1976). At Rangely, *in-situ* stress measurements and measurement of the frictional strength of the faults led to successful prediction of the pore pressure needed to induce earthquakes, thereby supporting the use of the effective stress law to the scale of earthquakes and faulting. However, not all aspects of the experiment were well explained, for example the occurrence of earthquakes far from the target fault, which required extreme hydraulic parameters using the conventional explanation. Modern thinking about elastic stresses could potentially solve these problems, however, the lack of geodetic data for the original experiment prevents a detailed analysis. Rangley also demonstrated that a well-characterized site, including tens to hundreds of observation wells, is an imperative. This included the analysis of the size of faults within the field area and minimized the risk of triggering a large earthquake. Armed with new technology in fault zone drilling and geodesy, a new generation earthquake experiment could more directly measure fault slip and fluid pressures both within the fault core as well as the surrounding damage zone, that should enhance our ability to determine where and when failure will occur.

Recent borehole experiments have successfully induced small earthquakes ($-4.5 < M_w < -3$) in a controlled way (Derode et al., 2015; Guglielmi et al., 2015; De Barros et al., 2016). Observations of the induced earthquakes have demonstrated that the physical processes that lead to runaway slip are complex and depend on the hydromechanical and frictional characteristics of both the fault and the surrounding rock. These experiments show that a small amount of dilatant aseismic slip can occur before seismic slip, and that earthquakes can be generated even in velocity strengthening material, which laboratory experiments suggested was unlikely (Guglielmi et al, 2015). Furthermore, several current microseismic experiments in underground mines are providing insights into the complexity in small earthquake nucleation (e.g. Yabe et al., 2015). Despite the exciting results of these studies, the earthquakes generated were limited to a small number of small magnitude events. Any change in physics from small to large earthquakes could not be captured in these experiments, and the effects of cumulative waste-water injection remain unconstrained.

Finally, the recent surge of earthquakes associated with hydrocarbon production and wastewater disposal offers new lessons. The frequency of earthquakes occurring in seismically quiet areas such as the

Midwestern US and western Canada is greater than has ever been previously recorded (Ellsworth 2013) and even moderate-sized earthquakes could prove hazardous in areas that are unprepared for seismic activity. Many of the recent earthquakes are induced by human activity, but although we know that fluid injection causes induced seismicity (Raleigh et al., 1976), we cannot predict exactly when and where a particular earthquake will occur – just as with tectonic earthquakes. The scientific community should be able to contribute to this problem by defining the stress and fluid pressure conditions that are necessary to cause earthquake slip, but the measurements necessary to make these predictions do not exist. Talks and discussions on induced seismicity at the SEISMS workshop mostly focused on the role of inherited structures and stress field characteristics in making an area more inclined to have induced seismicity. Some of the questions included: Are stress drops low in induced events (Sumy et al., 2017) or no different than tectonic earthquakes (e.g., Huang et al., 2017; Clerc et al., 2016)? What are pre-stress conditions on the fault within its seismic cycle, how do they affect induced events? What role do fault damage zones play in communicating fluid pressures over large distances (Hennings et al., 2012)? What metrics are there for tracking how close a fault might be to failure during fluid injection?

1.4. Necessary Components for an "Active" Earthquake Experiment

1.4.1 Essential Instrumentation

Recent fault zone drilling and other drilling projects have resulted in significant advances in borehole observatories and drilling capabilities. For instance, borehole instruments routinely include seismometers, thermistors, pore pressure sensors, and strain meters (Fulton et al. 2013; Chiaraluce et al., 2014). Increasingly, fiber optic cables are being emplaced within borehole casing and utilized as seismometers (Constantinou et al. 2016), strain meters and pressure meters (Cappa et al., 2006). To capture length scales appropriate for both the rupture tip region and fault slip patch dimension, observatory coverage across a wide range of scales will likely be required, so this type of instrumentation would be ideal for an active earthquake experiment. Finally, borehole observatories that exist on longer timescales (months-years) will need to carefully consider temperature and fluids at depth, including precursory monitoring.

1.4.2 Feasible Sites

Preliminary site discussion at the SEISMS meeting focused on what would make a site feasible from both a scientific and safety standpoint. As a group, a list of criteria was developed that would be necessary for a successful site including:

1. Faults that are well oriented in the current day stress field and possible to activate.
2. Detailed subsurface characterization, including 3D seismic imaging, determination of the stress and pore pressure fields, combined with surficial geologic mapping.
3. An area with low population density, yet developed infrastructure (such as an oil field).
4. Pre-existing and ongoing site monitoring.
5. Potential for collaboration from industry to take advantage of existing infrastructure and develop science priorities that can meaningfully contribute to hazard mitigation.

The specific sites discussed included places where induced seismicity is already occurring like Oklahoma and British Columbia, as well as the Basin and Range, USA, and oceanic transform faults. Both terrestrial and oceanic sites were viewed favorably for an earthquake experiment (Figure 2). Active experiments on the ocean transforms where frequent repeating events occur (McGuire et al., 2005) and continental faults where events occur much less frequently, can address different aspects of the initiation and rupture process. Also, logistical and observational constraints are very different for the two types of settings. Since there are different advantages and disadvantages for these two types of experiments, there were recommendations that proposals for both types of experiments should be in worked on in parallel. Although discussion was not focused on a specific site at this time, the importance of picking a site where detailed understanding of fault structure including the role of the damage zone in transmission of fluid pressures, number and thickness of localized slip zones, as well as friction strength, could be established before the active phase of the experiment.

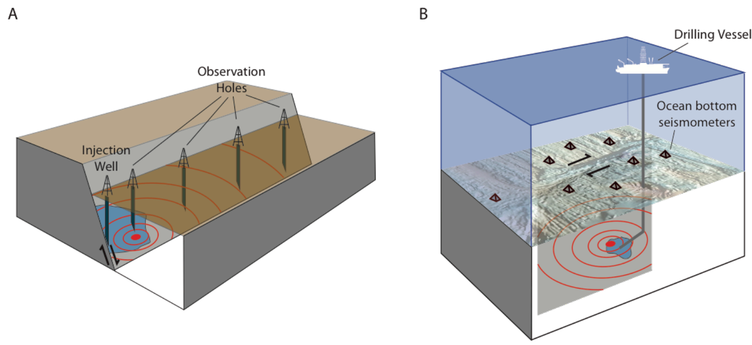

Figure 2. Potential target faults. A) Continental fault observatory. Fluids pumped at the injection well will trigger an earthquake that can be recorded with seismometers, temperature sensors, strainmeters, etc, at the observation holes. B) Oceanic transform fault observatory. Fluid injected from a ship would trigger an earthquake on the fault that would be recorded by a network of ocean bottom seismometers (OBS in grey pyramids). Observation holes may also be drilled in advance of the injection.

1.5 Societal Concerns

Safety and societal issues regarding potential induced earthquake experiments in various regions were prominent discussion topics throughout the workshop. The concept for the project would be to induce earthquakes through fluid injection, which would represent a hazardous outcome. However, there was recognition that understanding the causes of the many current human-induced earthquakes is an important issue for scientists to undertake. Given the largely unmonitored and uncontrolled way in which earthquakes are being induced in some regions, an experiment such as this would provide a valuable opportunity for the scientific community to provide some constraint on how to limit unintentional induced seismicity.

Past examples of active geologic experiments show that communication with local officials and the public will be central to a successful project, as well as evaluation of safety risks, which would be essential for any project that might produce felt earthquakes. Outreach and education efforts will be important for any active experiment because this will likely be a high-profile project in the public eye. This should be viewed as an opportunity to provide information about earthquakes and seismic hazards. Plans for outreach activities should be started along with development of science objectives, for example by engaging local members of the public to invest in the project by helping to articulate what questions should be answered with the experiment.

2. Workshop Outcomes and Future Directions

Participants identified three key questions at the workshop that should be targeted by the SEISMS project. They all depend on the measurement of stress, deformation, and pore pressure in the ultra-near field of an earthquake, and which therefore require a borehole observatory positioned close to the earthquake source.

1. *Can we accurately determine when and where an earthquake is going to occur once fluid pressure is elevated*?

   Many induced earthquakes are associated with wastewater injection or hydraulic fracturing operations, both of which elevate fluid pressure and reduce the effective stresses at depth, promoting earthquake occurrence. However, many injection wells do not appear to induce seismicity (e.g. Cornet, 2016; Rivet et al., 2016), some wells appear to induce earthquakes at significant distances from the injector (e.g. Yeck et al., 2016; Goebel et al, 2017; Keranen et al, 2014), and some wells that directly penetrate faults have little effect on stability (Hauksson et al., 2015). These results show that even though the Rangely experiment in the 1970s seemed to demonstrate that the effective stress hypothesis describes fault failure under *in-situ* conditions, it is still currently impossible to predict where and when an earthquake will occur, even within regions where fluid injection is taking place. This is partly because the mechanisms by which stress and pore pressure are transmitted to a fault are poorly understood. Direct fluid pressure increase and elastic stress perturbation have both been shown to be important for triggering earthquakes (e.g. Deng et al., 2016; Segall and Lu, 2015; Barbour et al., 2017), but which is more efficient, and therefore potentially more hazardous, is unknown. Induced earthquakes that occur far from an injection well indicate that fluid pressures are transmitted rapidly, highlighting the importance of complex fault zone hydrogeological structures. Furthermore, there is currently no consensus on how to predict what magnitude of earthquake could arise given a known stress or pore pressure perturbation to a fault (e.g., McGarr, 2014; van der Elst et al., 2016). An experiment to test the response of a fault to a controlled perturbation affecting a known volume in the subsurface could elucidate the conditions necessary to induce earthquake slip, and therefore determine the limits of water injection operations appropriate for preventing unwanted induced seismicity. Important advances in technology have occurred in the nearly 50 years since the Rangely experiment. Rangely included no geodetic instrumentation and therefore could not assess the role of elasticity or creep in inducing earthquakes. Modern, digital and dense instrumentation could provide a much higher resolution image of the earthquake locations that could address outstanding quandaries, such as the apparent location of the induced earthquakes kilometers away from the injection well.

2. *How do earthquakes nucleate?*
   Laboratory-derived friction laws such as the rate-and-state equations imply that a small amount of aseismic creep should precede an earthquake. Such a precursory phase has long been sought in observational data, including foreshock sequences (e.g. Kato et al., 2012; Chen et al., 2017)). More recently, geodetically-measured slow slip events are one of the more promising avenues of identifying an impending mainshock (e.g. Uchida et al., 2016). However, the scale of the precursory slip patch may be quite small, 10 m or less, and the ability to measure such a signal therefore likely depends on *in-situ* measurements. In such a case, the larger scale slow slip and foreshock sequences that are sometimes measured with surface instruments would be the result of more complex interactions between slip on the future rupture interface, the surrounding damage zone, potential fluid pressure changes, and heterogeneity of all of these properties along the fault (e.g. Savage et al., 2017).

3. *What controls earthquake propagation and arrest?*
   All earthquakes nucleate, but not all grow to large magnitudes. This implies that some earthquakes do not propagate significantly and arrest at small magnitudes instead. Rupture propagation is thought to be a function of the initial conditions in the source region, the constitutive laws that govern frictional sliding, and the geometrical properties of the host fault. The stress field and pore pressure distribution in and around a fault are heterogeneous, and the physical characteristics of faults such as roughness and damage zone characteristics are spatially variable. Constraining all of these parameters prior to an induced earthquake would be challenging, but near-field observations of the rupture tip zone would provide an unprecedented view into the underlying physical processes.

Because the answers to the three questions outlined at the SEISMS meeting are fundamental to predicting when and where large earthquakes will occur, the workshop participants were in agreement that an earthquake experiment by fluid injection should be pursued. The next order of business is to establish potential industry partners and have a more complete discussion of potential drilling targets. More immediately, the discussions began at the SEISMS meeting are being continued at larger conferences including the Continental Scientific Drilling Coordination Office (CSDCO) annual meeting and the 2017 American Geophysical Union (AGU) Fall Meeting.

5. Papers from this workshop

Savage et al., 2017. "Workshop Report: Scientific Exploration of Induced Seismicity and Stress (SEISMS)", Scientific Drilling. (this report)

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